SIM external metrology beam launcher (QP) development

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ABSTRACT

Visible interferometry at μarc-second accuracy requires measurement of the interferometric baseline length and orientation at picometer accuracy. The optical metrology instruments required for these interferometers must achieve accuracy on order of 1 to 10 picometers. This paper discusses the progress in the development of optical interferometers for use in distance measurement gauges with systematic errors below 100 picometers. The design is discussed as well as test methods and test results.

Keywords: laser interferometry, beam launcher, external metrology, quick prototype, QP

INTRODUCTION

The Space Interferometry Mission ("SIM") satellite will use parallax to measure distant stars, using the apparent angle relative to "fixed stars" as observed from different points on the earth's orbit around the sun. The angular resolution of these astrometric measurements depends in part on the accuracy with which metrology gauges can measure the satellite's distortions for later data correction. It's a simple problem of "similar triangles": the uncertainty (including the metrology gauge's accuracy) is to the satellite's baseline length as the diameter of the earth's orbit is to the distance of the farthest measurable star.

To measure the diameter of the Milky Way, one needs metrology gauges with tens-of-picometer resolution, several orders of magnitude more accurate than any now commercially available. A gauge consists of a laser source (infrared, so that any stray light won't wash out the faint light of distant stars; shared between all the gauges so as to remove laser drift), the beam launcher (optics), and the processing electronics ("phase meter"). JPL and Lockheed Martin have designed, built, and tested various launcher concepts and configurations recently,[1,2] with the "lessons learned" from each used to improve the subsequent designs. This paper reports on the "QP" (or "Quick Prototype") launcher that was developed to test and verify some of the past lessons.

Figure 1 shows the basic heterodyne interferometer. The heterodyne configuration is used because even minor intensity fluctuations in laser power give unacceptably large phase shifts in the alternative homodyne configuration. A laser beam is routed into an optical fiber and then split. Each beam is frequency-shifted by an acousto-optic modulator ("AOM"), with some convenient offset

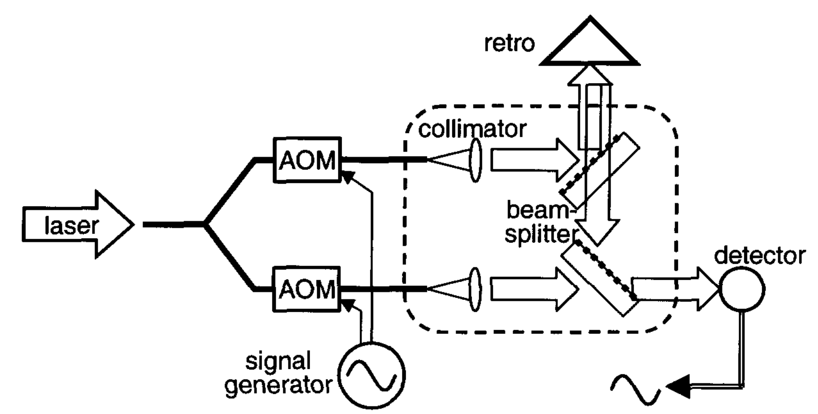

Fig. 1: Heterodyne Interferometer

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frequency between them. The laser light is then routed to the beam launcher (within the dotted line) by an optical fiber network.

Inside the launcher, the beams exit the fibers and are collimated (for example, by lenses), and the two beams then are routed by beam-splitters (half-reflective mirrors). One beam (the Measurement Beam) interrogates the retro, and then upon return is mixed with the other beam (the "local oscillator", or LO beam) to create the heterodyne (beat) signal. This is then detected and processed, and the resulting signal is compared with the signal that drove the AOMs.

A problem with this configuration is that it is not accurate enough for SIM: if the optical fiber were stressed by a slight bend, or if the temperature of an optic were to change slightly, this would cause a phase shift that may be small, but that nonetheless is large compared to picometers. Figure 2 shows a fix: pick off part of the laser light as a "Reference Beam". Beam "A" passes through all the fiber distribution networks and collimators, and then a part of the laser beam is broken off and mixed with the LO beam to recreate the beat signal. The rest of the "A" laser beam is the Measurement Beam that interrogates the retro. Each beam is mixed with the LO beam ("B") and routed to a detector. The resulting signals are compared in the phase meter to give the measurements. This requires about twice as much electronics and optics, but it does measure and compensate for most of the phase errors in the fibers and optics.

Even this is not adequate for SIM. If the path lengths within optics do not match exactly, then even modest changes in temperature can introduce errors. (For example, in the layout in Fig. 2, both beams "A" and "B" pass through two beam-splitter optics before mixing for the measurement channel, but in the reference channel beam "A" goes through an extra piece of glass. Even a milli-Kelvin temperature change could cause a 100 pm error.) Other considerations are that the different optics all have to experience exactly the same temperature (or at least maintain a constant difference), and the relative positions of the optics have to be stable to better than the overall required picometer accuracy. After several design iterations, it was determined that the best approach is to keep the Reference and Measurement Beam paths common as much as possible.

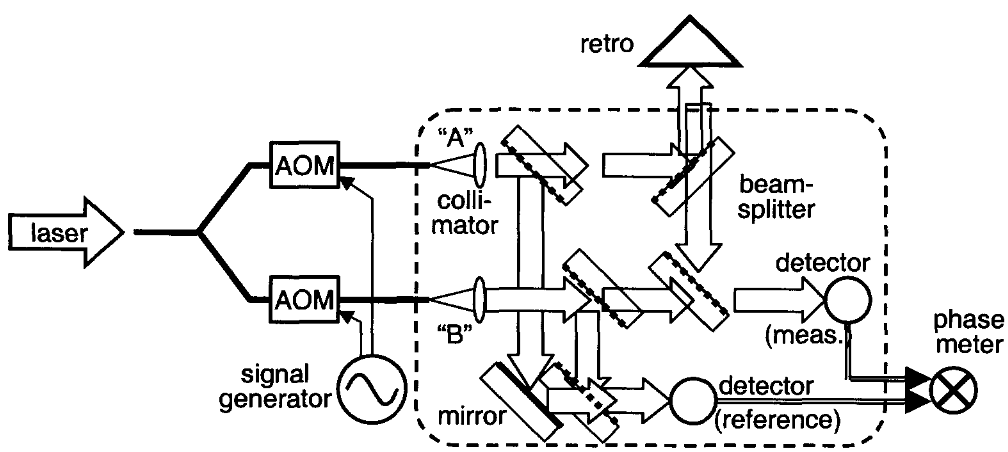

Fig. 2: Interferometer with Reference Channel

In the design iteration prior to QP, we built the "Athermal Launcher" that appeared to meet all of the requirements: common paths, matched path lengths, and temperature compensated. The design used polarization tricks to keep the various beams separate while still following the same paths. Once it was built, however, it was discovered that, hidden under all the other errors that were now suppressed, there was a small, but still too large, nanometer-class error. Called "the cyclic error", it varied with changes in measured distance with a period of lambda/2. It was determined that a small fraction of the laser light that was supposed to go out and interrogate the retro instead took a short-cut through a polarizing beam-splitter and skipped that step. The phase of the true Measurement Beam varies with distance to the retro while the short-cut phase did not, and so the stray light sometimes led or lagged the true signal as the distance changed, introducing the cyclic error. If the short-cut path were constant, one might be able to calibrate and compensate for the cyclic error. However, the short-cut's phase will vary slightly with minor temperature changes, and so a correction that is valid at one time might make the answer worse at others.

There are two approaches to dealing with the cyclic error: (1) reduce it by signal processing ("cyclic averaging"), or (2) reduce or eliminate the stray beam-paths. The cyclic averaging approach involves dithering and the averaging of multiple readings, requiring considerable electronics and extra time, thereby reducing the data throughput considerably. The goal became to reduce the stray signals.

Analysis showed that the isolation between signal and stray beams needs to be better than 80 dB. The Athermal Launcher used polarizers to separate the beams, which may be good to a tenth of a percent, but that gives only 30 dB of isolation. If we truly understood the cause of cyclic error, we felt we should be able to design a launcher without cyclic error. We built the Quick Prototype Launcher to demonstrate that.

THE QP CONCEPT

Figure 3 shows the beam paths in the QP Launcher. One of the laser beams (beam "A") enters via a fiber at the top of the sketch and is collimated. (The sketch shows lenses, but the actual design incorporated parabolic reflectors.) The beam hits a Double-sided Mirror and is reflected off to the left, to interrogate the retro "corner cube 1" (CC1). QP has a "racetrack" configuration – the beam measures the distance between two retros by making a loop: the beam goes to the first corner cube and hits it off-center; the reflected beam is offset and goes past the launcher to hit the second corner cube off to the right; and the beam reflected by that is offset again and now lines up with the entrance aperture mask "A". The beam hits the back side of the Double-sided Mirror and proceeds down. The light of beam "B" (the LO beam) is collimated and mixed with the Measurement Beam at the beam combiner, and the resulting heterodyne beam is sent off to detector "D1".

The Reference Beam is picked out by means of a hole in the Double-sided Mirror: part of the beam goes straight through rather than making the loop. (This causes a shadow in the out-going beam, as shown, although it is somewhat filled in by diffraction by the time it gets back.) The Reference Beam is also mixed with the LO beam, and the resulting mix is separated off and sent to detector "D2". A pair of shallow wedges form a "Risley Pair" for precise alignment.

Note that, except for the racetrack between the retros (and the very short distance through the Double-sided Mirror itself), the Measurement Beam and the Reference Beam follow the same path. This "Common Path Heterodyne Interferometer (CoPHI)" configuration allows the reference channel to measure and remove nearly every error source.

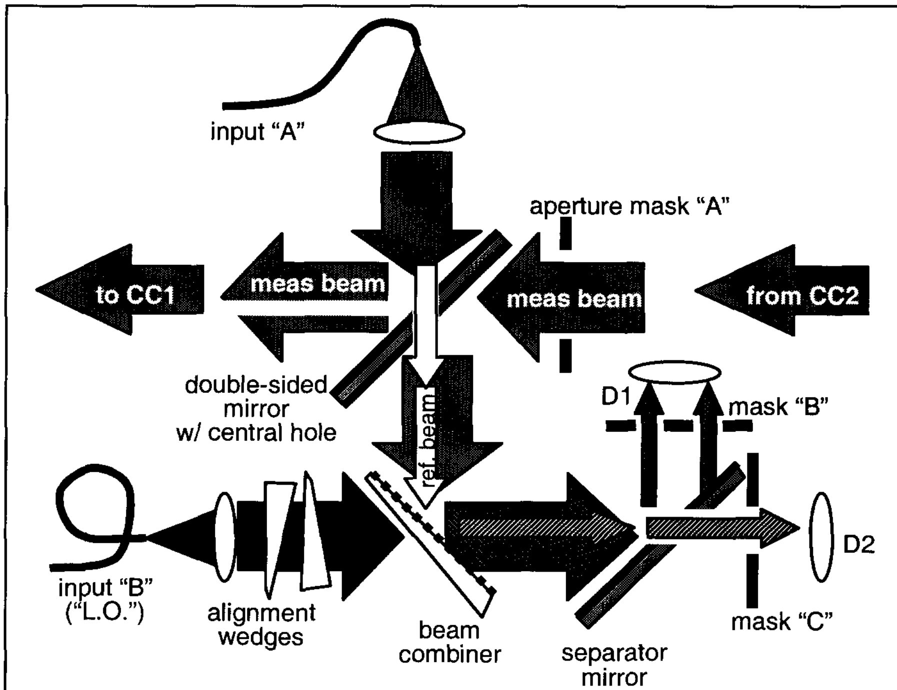

Fig. 3: Schematic of QP Launcher

To keep the cyclic error acceptably small, better than 80 dB isolation is needed, and it doesn't matter if the source of contamination is polarization bleed-through, diffractive cross-talk, or stray reflections. Diffraction was modeled to assure that not too much of the Measurement Beam would diffract into the reference channel or vice versa. And stray-light reflections were tracked to assure that they too would not corrupt the signal. Various masks were used to keep the Reference Beam and Measurement Beam spatially isolated.

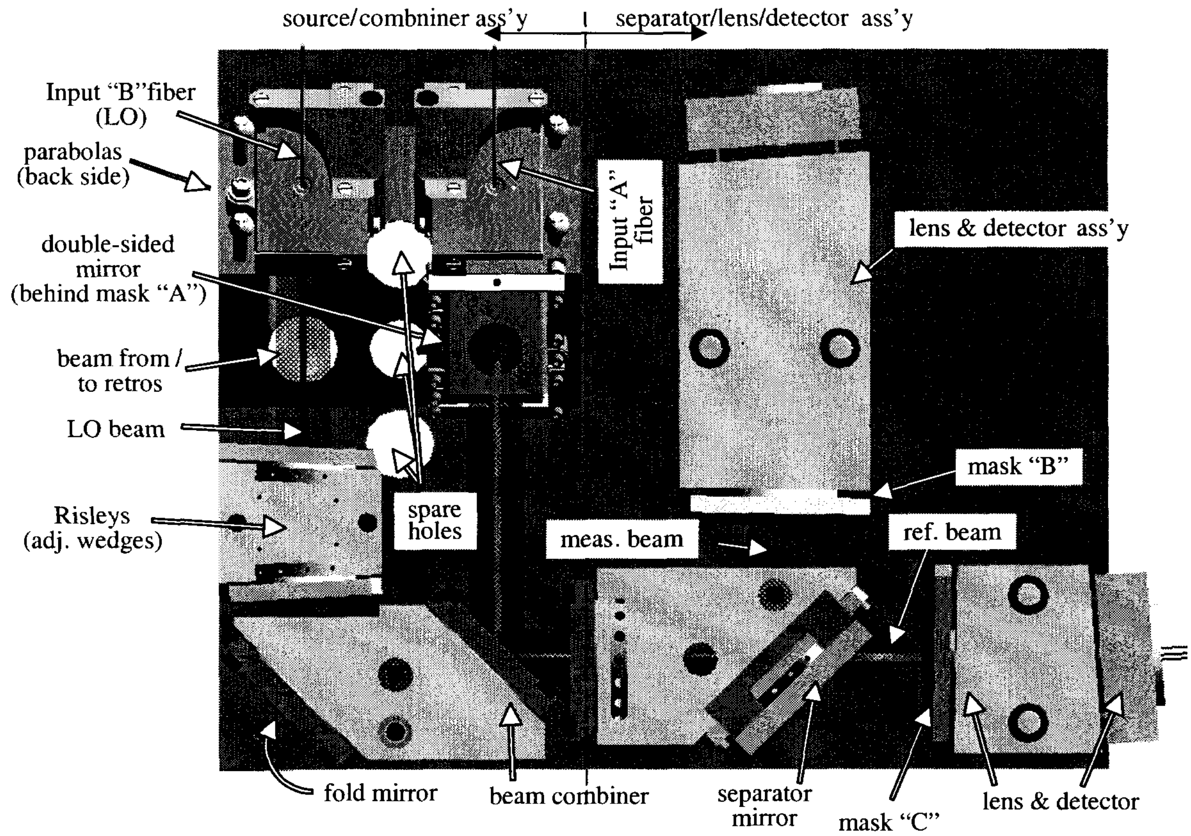

Fig. 4: Solid-model rendering of OP Launcher

THE QP DESIGN

Figure 4 shows the solid-model rendering of the QP Launcher design. The beams are collimated with parabolas located on the back side. The LO beam runs down the left side of the drawing, is folded by the fold mirror, and then goes right along the bottom. The "A" beam starts at the top mid-left and also goes down a ways, then hits the Double-sided Mirror (behind the "mask A" holder). The Reference Beam continues through the mirror, but the Measurement Beam reflects off of the Double-sided Mirror and heads off to Retro #1 situated behind the gauge. The Measurement Beam is offset by the retro and reflected back, passing through the left-most hole to Retro #2 situated in front of the gauge. The beam is then offset again and reflected back to the gauge, passing through Mask "A" and hitting the back side of the Double-sided Mirror. The Measurement and Reference Beams are now again aligned and roughly collocated, and they head down to the beam-combiner to be mixed with the LO beam. The right half of the gauge has the Separator Mirror (to fold the Measurement Beam while passing the Reference Beam), and two sets of masks, lenses, and detectors.

The collimators use reflective parabolas (Fig. 5), thereby avoiding the air/vacuum refocusing issue of refractive optics. The parabolas are on-axis: the end of the optical fiber is placed at the focus, which is located in a hole in a fold mirror. The light fans out to the parabola, is reflected back as a collimated beam, and then reflects off of the fold mirror. The optical fiber (and associated ferrule and mirror hole) create a hole in the collimated beam, but since the double-sided mirror also has a hole for the reference beam, the central portion of the beam is corrupted anyway and has to be masked out. Figure 6 shows the calculated beam intensity pattern back at the double-sided mirror: the left half showing the pattern resulting

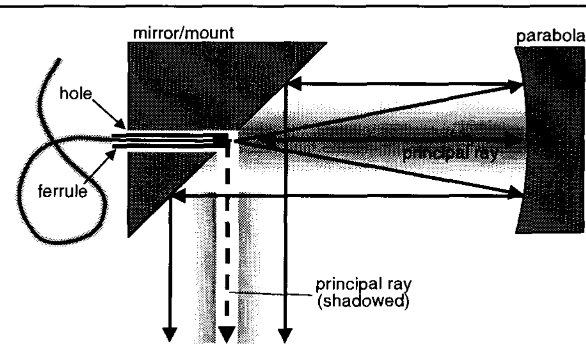

Fig. 5: Diffraction-modeled beam patterns

from the shadow of the two holes, and the right half showing how the beam is masked before it is directed on to the detector.

Figure 7 is a photograph of a completed unit. The collimators are in the foreground, with the fold mirrors on top and the parabolas on the back side. The lens/detector assemblies are towards the left and back of the photo. The measurement beam would head down from the back side of the unit to the first retro, then be reflected back up through the unit to the second retro, and then back to the double-sided mirror (as shown by the arrow). Virtually every component in the QP Launcher was made of zerodur or invar to minimize thermal drift.

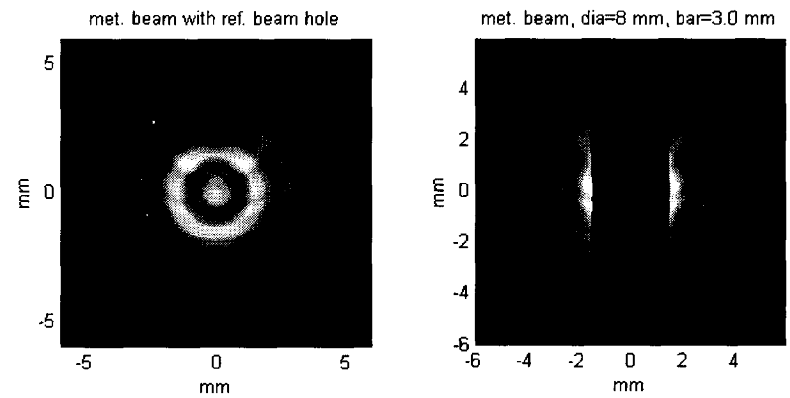

Fig. 6: Diffraction-modeled beam patterns

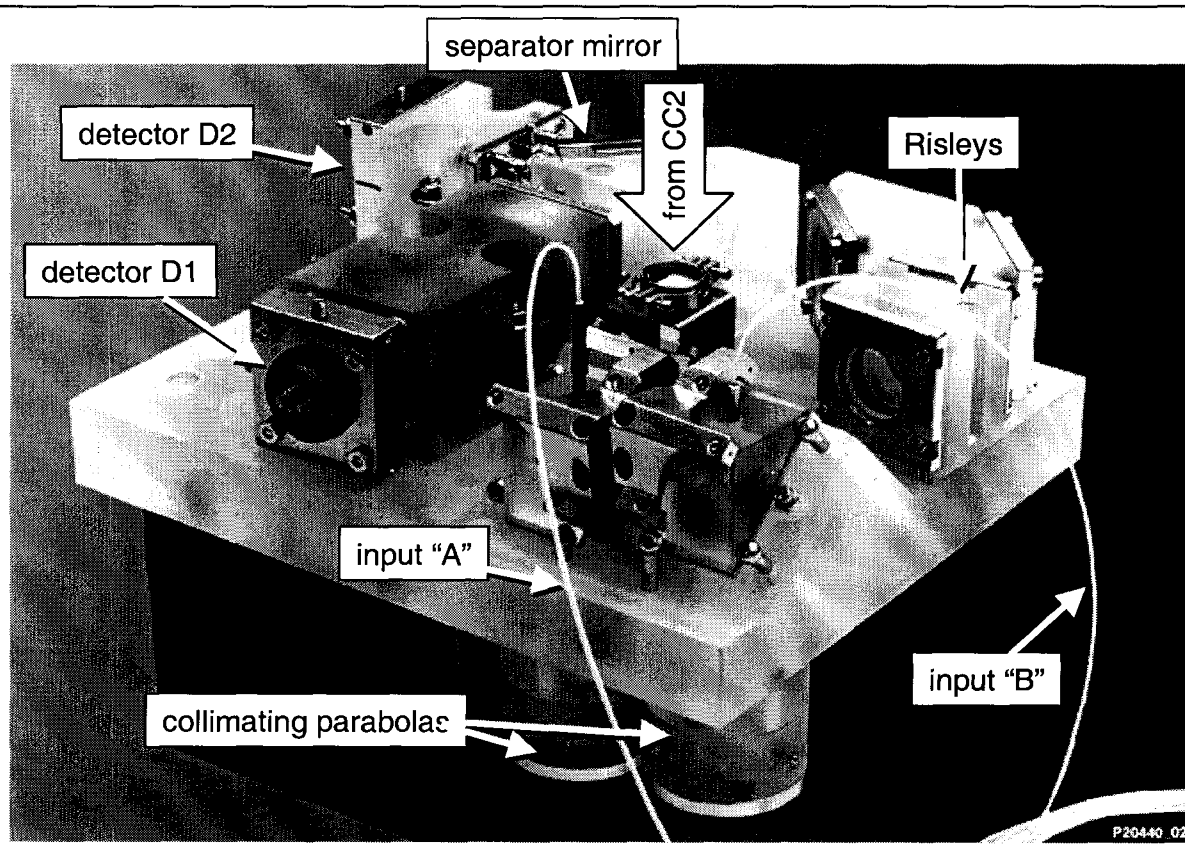

Fig. 7: the QP Launcher

CYCLIC ERROR TESTING

The QP Launcher was designed and constructed to verify that we understood the source of the cyclic error in prior design iterations. One way to test for cyclic error is to use the gauge to measure the distance between two retros, as shown in Fig. 8, and then very precisely move one of the retros and look for inconsistencies. However, if inconsistencies were uncovered, it would be unclear if it were because of cyclic error or because of an error in the precision of the retro motion.

An easier approach is to move the retro linearly at a uniform rate, and then take the Fourier transform of the resulting measurement. If the gauge is perfect and the motion perfectly uniform, the measurement would change uniformly and the Fourier transform would be smooth. Any errors in the motion show up as various bumps or dips in the transform, but the cyclic error shows up at only those frequencies corresponding to the velocity of the retro divided by half the laser wavelength.

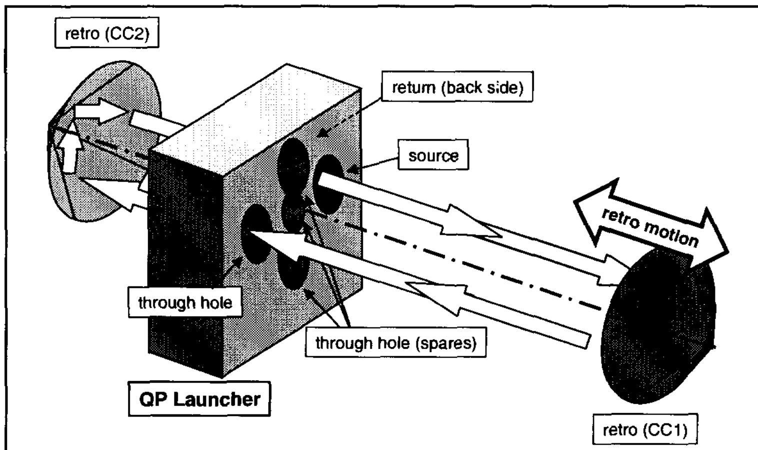

Fig. 8: One-gauge test setup

The QP Launchers are configured so that two gauges can simultaneously measure the distance between retros, as shown in Fig. 9. The second gauge is rotated 90° relative to the first, and each gauge's beam loops out and back through the spare holes in the other gauge. Both gauges measure the distance as the retro is moved, and the difference of these measurements is then Fourier transformed. The irregularities in retro motion are common to both measurements and are substantially removed by the differencing, but the cyclic errors each have an arbitrary phase and in general don't cancel out.

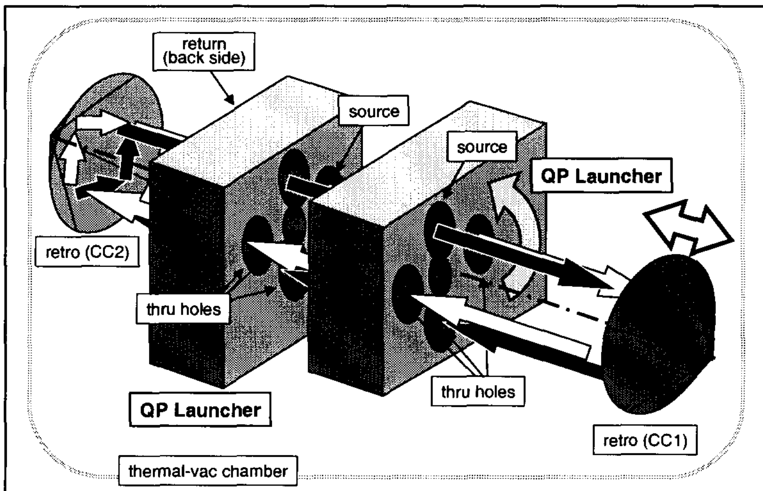

Fig. 9: Two-gauge test setup

Figure 10 shows the Fourier transform of an early set of test measurements. The retro was moved at a rate that generates the cyclic error at 43 Hz. As can be seen in the curves, there is a peak there in the reading from each gauge and in the difference. The measurements indicate that the cyclic error is below 100 pm rms, which was the goal of this experiment. Later detailed analyses indicated that some of the cyclic error resulted from electronic cross-talk, and once that was eliminated, the measured cyclic error was found to be roughly 25 pm rms.

The diffraction model that generated the beam patterns of Fig. 6 also calculated the leakage of the Reference Beam into the measurement channel and the Measurement beam into the reference channel. The model then calculated the mixing efficiencies, and from those the expected cyclic error. The model indicated that the "as-built" QP Launcher design should have a cyclic error of about 25 pm rms. This validated the model, and also indicated that the setup did not have any other contributors to the cyclic error, such as from scattered stray light. The model was then used to optimize various mask dimensions to further reduce the cyclic error while still maintaining adequate laser power on the detectors.

THERMAL EFFECTS

Once we had the "Two Gauge Test-bed" functional, we could use it to study other launcher properties as well. While the QP Launcher design was not optimized for thermal drift, nonetheless the drift could be modeled and then compared with experimental results. (The configuration is relatively insensitive to "soak temperature", but has a known susceptibility to thermal gradients. The next generation design remedies this flaw.)

Figure 11 shows the Two-Gauge setup. This photo shows the two QP Launchers between the two corner cubes, inside a thermally controlled vacuum chamber. The left QP is wrapped in multi-layer insulation (MLI) with strategically placed strip and plate heaters. The chamber was pumped down and the gauges allowed to reach equilibrium. Distance data collection began. The one launcher was then heated, and the difference in distance readings as a function of temperature was plotted (Fig. 12). Thermal modeling was done (Fig. 13) to examine gradients. (The gradients were unavoidable as the MLI had to have openings for the measurement beams, through which heat leaked to the cold of the thermal-vac walls.) The observed shift in the measurement differences (7.7 nm/°K) compare quite well calculated shift for the temperature excursions and gradients experienced.

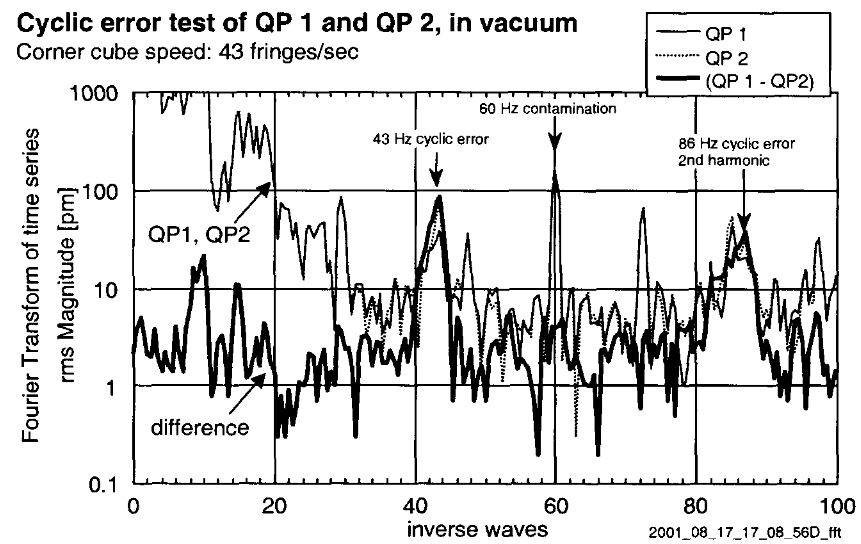

Fig. 10: Fourier transform of QP measurement data

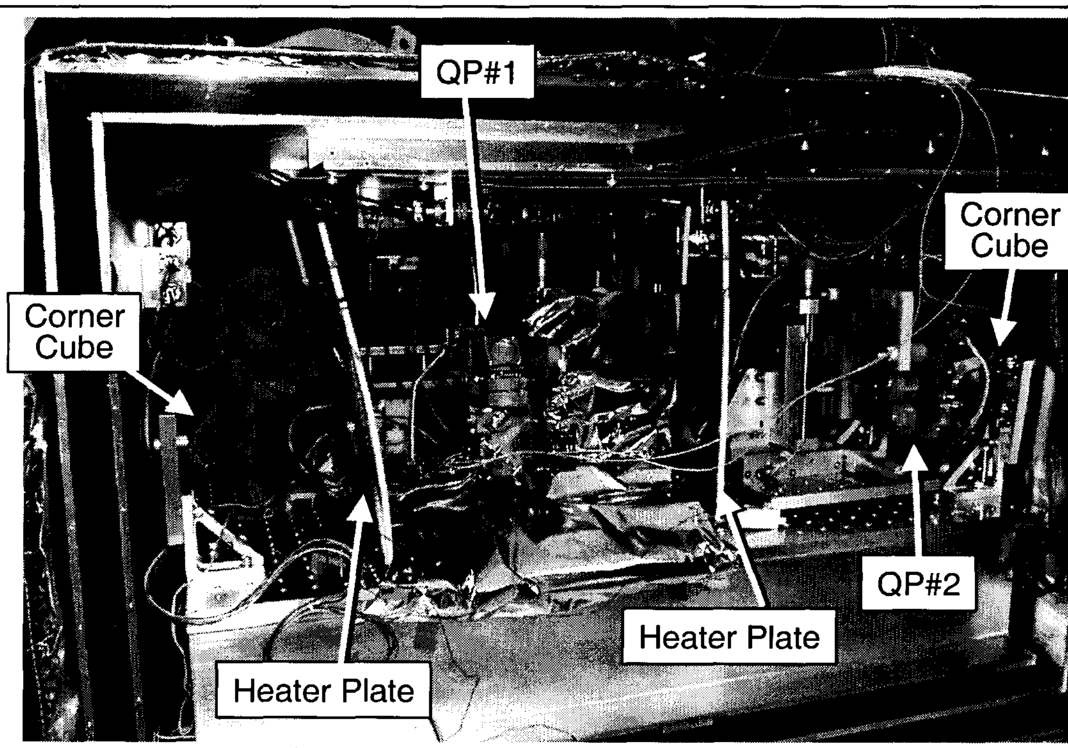

Fig. 11: Two-gauge test setup in thermal-vac chamber

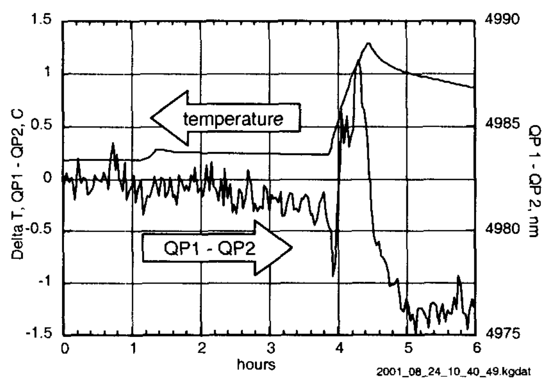

Fig. 12: Thermal data

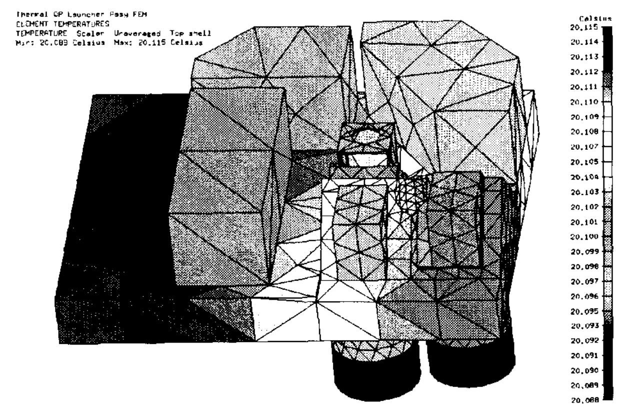

Fig. 13: Thermal model

CONCLUSIONS

We have built about a dozen QP Launchers now: they are not good enough for flight, but they are better than any other beam launcher we have and they are suitable for a number of demonstration test-beds. The cyclic error is understood and can be controlled, and the thermal properties of the launcher can also be modeled to satisfactory resolution. We have also learned a number of lessons that are being incorporated into the next generation of launcher design: look for us to describe a flight-worthy picometer-class gauge at the next conference!

ACKNOWLEDGEMENT

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